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THE RESULTS OF TWO YEARS TESTING IN REAL SEA OF WAVE DRAGON

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ABSTRACT

The Wave Dragon is an offshore wave energy converter of the overtopping type. It consists of two wave reflectors focusing the incoming waves towards a ramp, a reservoir for collecting the overtopping water and a number of hydro turbines for converting the pressure head into power.

In the period from 1998 to 2001 extensive wave tank testing on a 1:50 scale model was carried out at Aalborg University, Denmark and University College Cork, Ireland. Then, a 57 x 27 m wide and 237 tonnes heavy (incl. ballast) prototype of the Wave Dragon, placed at the Danish Test Station for Wave Energy, was grid connected in May 2003 as the world's first offshore wave energy converter.

The Wave Dragon prototype is fully equipped with hydro turbines and automatic control systems, and is instrumented in order to monitor power production, wave climate, forces in mooring lines, stresses in the structure and movements.

In the period May 2003 to January 2005 an extensive measuring program was carried out, establishing the background for optimal design of the structure and regulation of the power take off system. Planning for deployment of a 4 MW power production unit in UK by 2007 is in progress.

INTRODUCTION

Wave Dragon marks a significant breakthrough towards commercial exploitation of the abundant energy concentrated in ocean waves. Whereas previous wave energy converters have either failed to operate or only provided limited potential for electricity generation, the seagoing trial of the Wave Dragon prototype has proven its offshore survivability for more than 15,600 hours and verified the potential for commercial feasibility with large scale power generation below the costs of offshore wind power.

Developers of wave energy converters face a series of major challenges. First of all they have to develop machinery that can operate and survive in this very rough environment. Secondly one has to optimise operation and maintenance systems to make wave power plants a viable solution. Wave energy converters have to compete with other renewable energy technologies, and it has now become obvious that wave power can be much cheaper than for instance photovoltaic power. There are good reasons to believe that wave power in a few years time will be a serious competitor to offshore wind power.

WAVE DRAGON

Wave Dragon is an offshore wave energy converter of the overtopping type where each unit will have a rated power of 4-10 MW depending on how energetic the wave climate is at the deployment site. As part of the development activities towards a full size production plant by 2007 a grid connected prototype of the Wave Dragon has been tested at the Danish Test Station for Wave Energy in the inlet Nissum Bredning behind the North Sea (a scale 1:4.5 of a North Sea production plant).

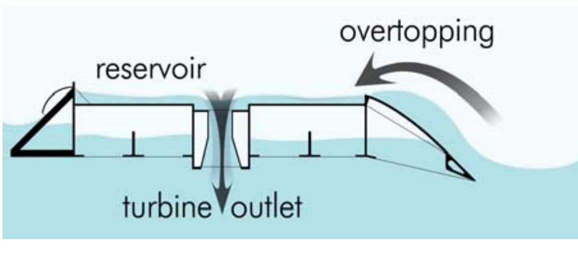


Figure 1: The basic principle of the Wave Dragon: 1) waves overtopping a ramp, 2) water stored in a reservoir above sea level and 3) water discharged through hydro turbines. Wave Dragon floats on open air-chambers used to adjust floating level

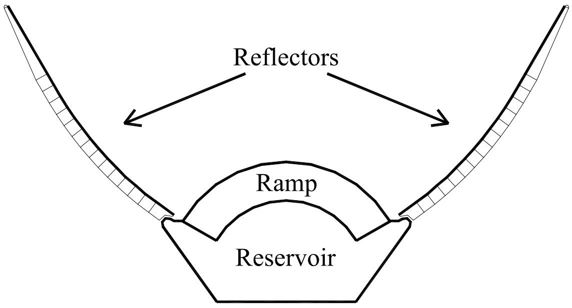


Figure 2: Main components of the Wave Dragon

Wave Dragon consists of three main elements:

- Two patented wave reflectors focusing the waves towards the ramp, linked to the main structure. The wave reflectors have the verified effect of increasing the significant wave height substantially and thereby increasing energy capture by 70 % in typical wave conditions.
- The main structure consisting of a patented doubly curved ramp and a water storage reservoir.
- A set of low head propeller turbines for converting the hydraulic head in the reservoir into electricity.

Figure 3: Wave Dragon from the sea.

HYDRAULIC BEHAVIOR

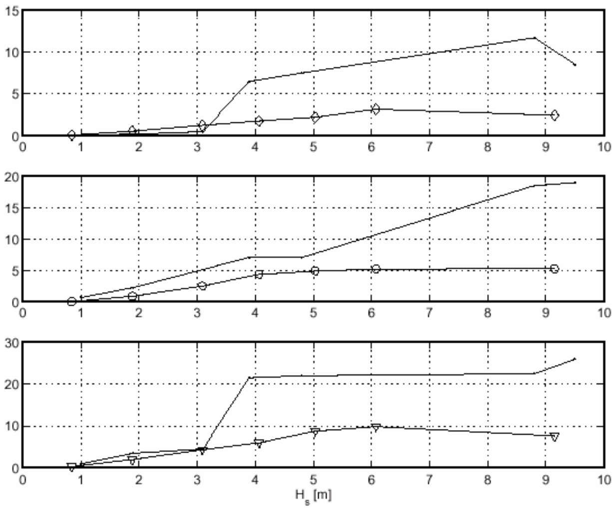


Figure 4: Heave, surge and pitch as function of the sea states (H_s meters in full scale)

The hydraulic performance of the Wave Dragon has been optimized through numerical modelling and the use of small scale models tested in wave tanks.

The first generation of the device showed too high heave, pitch and surge as the first mode of movement for the device was too close to the wave period at high sea states, see upper curves in figure 4.

The 1:50 scale model was then modified and satisfactory results were obtained (lower curves in fig. 4).

The scale 1:4.5 prototype has the same geometry and in accordance to the model laws similar results should be obtained. Only the open air chambers could not be modelled in strict similarity, due to the constant compressibility of the air. The results are shown in figure 5 and 6.

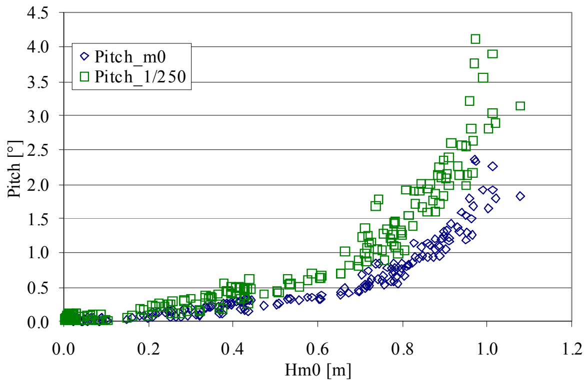


Figure 5: Pitch as function of the actual sea states (H_s (=H_{m0}) in full scale to be multiplied with 4.5)

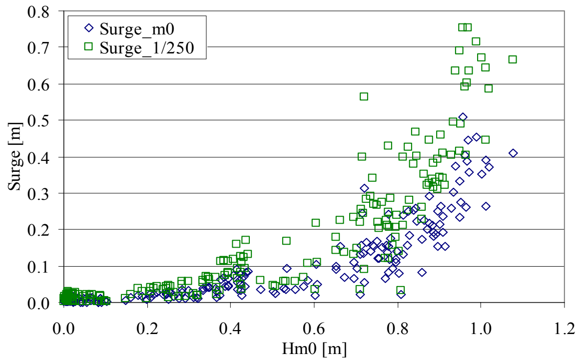


Figure 6: Surge as function of the actual sea states (H_s (=H_{m0}) and surge in full scale to be multiplied with 4.5)

When comparing the two set of graphs it is obvious that the maximum surge and pitch values in the scale 1:4.5 test series are only half of those measured in the scale 1:50 scale test series.

It appears that the air chambers are acting as a cushion, improving the hydraulic behaviour and thus reducing the surge and pitch motions.

Figure 7: The open air chambers can not be modelled in small scale testing.

SURVIVABILITY

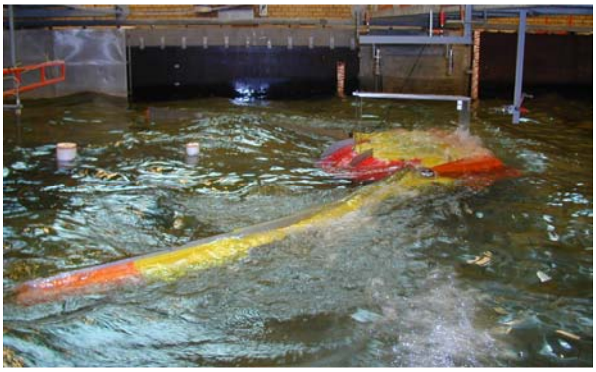


Figure 8: In high sea states the Wave Dragon just allows the waves to spill over.

The basic mechanism of Wave Dragon to survive extreme waves is to let the waves overtop the whole device. Production is still possible in these conditions, and the mooring forces are not increasing unpredictably. 1:50 scale testing results have been confirmed by the prototype testing in real sea.

Figure 9: Over spill at the prototype during a storm with wind speed of 25 m/sec.

MOORING FORCES

Measurements of mooring forces in both model scale and prototype have been performed and show good correlations, as illustrated in figure 10. The prototype experiences underline the importance of having an elastic mooring system in order to avoid high snap loads.

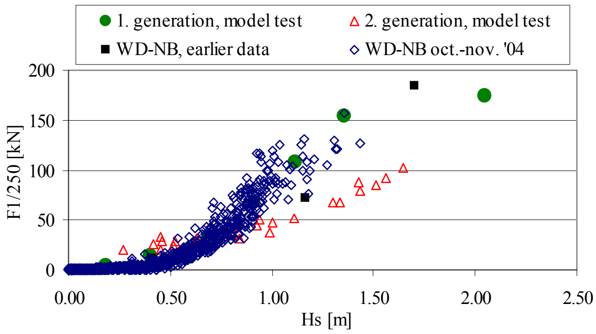


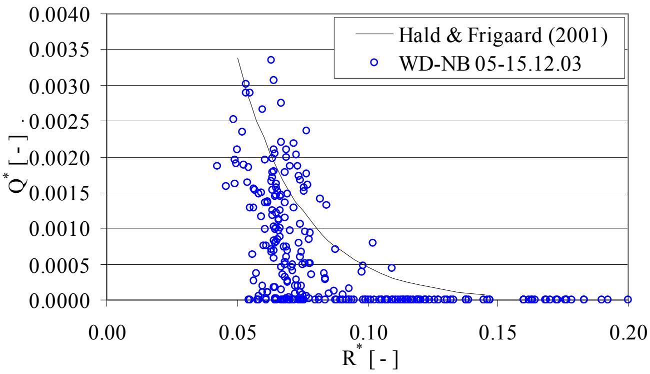
Figure 10: Comparison of mooring forces in terms of F1/250 (average of the 1/250 largest peaks) measured during 1:50 scale tests and prototype measurements (1:4.5). H_s is given in prototype scale.

OVERTOPPING

The test series with the 1:50 scale model have lead to an overtopping expression (Eq. 1) by Hald & Frigaard. As indicated in Figure 11 the measured prototype data compares well with the expression based on laboratory tests. The general scatter and the data points falling below the prediction line can be attributed to the following reasons:

- Ideally, the buoyancy control system on board should keep the reservoir level at all time. This has not been the case during all the test runs. The regulation of the buoyancy system is still being optimised in order to obtain more stability.
- When the crest freeboard has been low compared to the wave height the limited capacity of the turbines and reservoir occasionally lead to spilling of overtopped water.
- Due to the current mooring configuration at the test site Wave Dragon has not been able to align it self up against the waves at all times, and misalignment with the wave direction decreases the overtopping rate.
- Measuring uncertainties, especially on the measurement of the floating level and thereby the crest freeboard. Some drifting of the pressure measurements has been experienced, mainly due to marine growth on the transducers.

However, it is reassuring that there are points above the prediction line, as this indicates that the overtopping expression can be exceeded under certain circumstances. Thus, the overall picture is that the overtopping expression is realistic in normal operation, i.e. when the reservoir is level and not overflowed and Wave Dragon is fairly aligned towards the waves.



(Eq. 1) $$Q^* = 0.025\exp(-40R^*)$$

where

$$Q^* = \frac{q\sqrt{s_{op}/2\pi}}{\sqrt{gH_s^3}L}$$

$$R^* = \frac{R_c}{H_s}\sqrt{\frac{s_{op}}{2\pi}}$$

q = discharge rate due overtopping [m^3/s]
H_s = significant wave height [m]
L = ramp width [m]
s_{op} = wave steepness, $s_{op} = H_s/L_{op}$ [-]
L_{op} = deep water wave length, $L_{op} = \frac{g}{2\pi}T_p^2$ [m]
T_p = Peak period [s]
R_c = Crest freeboard relative to MWL [m]

Figure 11: Comparison of preliminary prototype data and overtopping expression

POWER TAKEOFF SYSTEM

The potential energy of the water stored in the reservoir is exploited by a set of low-head turbines. The turbines have been specifically developed for this application, meeting the following requirements:

- The turbine head ranges from 0.4 m to 4.0 m, which is not only on the lower limit of existing hydro power experience, but also an extremely wide variation.
- Due to the stochastic time distribution of the wave overtopping and the limited storage capacity, the turbines have to be regulated from zero to full load very frequently.
- The turbines have to operate in a very hostile environment, with only a minimum of maintenance being possible on an unmanned offshore platform.

From the above, it was decided that the turbines had to be as simple and rugged as possible, with an absolute minimum of moving parts. Thus, a design with both fixed guide vanes and fixed runner blades has been chosen. Efficient operation over the wide discharge range is ensured by using between 12 and 16 relatively small turbines that can be switched on and off individually rather than a few large turbines. In order to grant a high efficiency throughout the wide head range, the turbines are operated at variable speed, using inverter-controlled and directly coupled synchronous permanent magnet generators. In order to keep the generator dimensions and cost low, the turbine design aimed a achieving a high specific speed; trying to attain a high unit discharge at the same time, which makes for a compact turbine.

The turbine has been designed to meet these requirements, making extensive use of CFD simulations. A model turbine has then been tested at TUM, and was found to give 90.1% efficiency at model scale.

For reasons of cost, the scale 1:4.5 prototype has only been equipped with 1 siphon inlet and 6 cylinder gate turbines, see fig. 12. 6 further turbines have been substituted with a set of three 'dummy turbines'. The latter are in fact discharge valves which have been exactly calibrated to release twice the flow rate of one turbine each.

Figure 12: The six axial propeller turbines being assembled at Kössler GmbH

While the siphon turbine has been already been installed before the deployment of the prototype, the cylinder gate turbines have only been installed at sea in September 2003. During the first year of operation, two problems became apparent:

- The seals of the thrust bearings, which were a standard hydro turbine design failed in the sea environment, with subsequent damage to the bearings.
- The draft tubes of one turbine group had been painted with a standard epoxy paint system. These had developed extensive marine growth, reducing the turbine efficiency.

The draft tubes of the other turbine group had been treated with a non-toxic silicone based antifouling paint and were still clean after being in the sea for one year. The bearings have since been re-designed and the turbines have been re-assembled after coating all draft tubes.

Fig. 13 shows three of the turbines on board of the prototype. The turbines have been re-commissioned in September 2004 and have been in continuous operation since then, without any further problems. The power delivery from the generators was found to agree perfectly with the predictions.

Figure 13: turbines on board of the prototype

POWER PRODUCTION

The optimisations including overall structural geometry, focusing especially on reflector design and the cross section of the ramp has almost doubled the energy capture compared to the 1. generation design.

Results from the power production has still not been analysed in full depth. Figure 16 is showing how the production follows the turbine steps very well.

WAVE CLIMATE

The 1:4.5 scale Wave Dragon prototype has been deployed at the Danish Test Station for Wave Energy in Nissum Bredning, see fig. 14. In this fjord, the wave heights are reduced 1:4.5 compared to the North Sea, which makes it ideal for testing prototypes.

The wave climate at the wave test station was predicted in 1998. However, the actual wave climate registered during the more than 2 year test period had shown higher waves than anticipated, as shown in figure 15.

Figure 14: The Danish Test Station for Wave Energy in Nissum Bredning

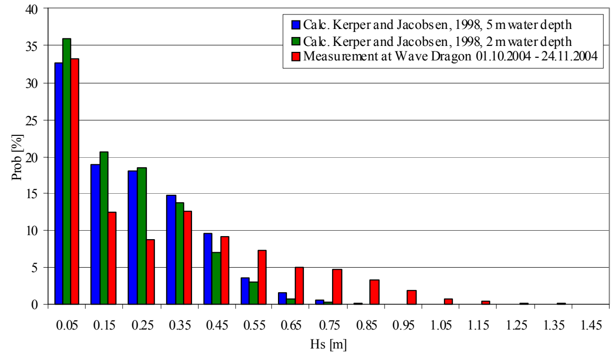


Figure 15: Wave height H_s distribution at the Danish Test Station for Wave Energy

SCALING UP

Wave Dragon can be constructed in any size. Table 1 is giving the optimal size and yearly production for different wave climates, based on the presently measured efficiency and the calculated construction costs.

There is no upwards restriction in Wave Dragon unit size as the efficiency steadily increases with the physical size. The chosen size at an actual wave climate is solely a result of a cost benefit calculation.

The Wave Dragon technology is in the short term expected to be economically competitive with offshore wind power in wave climates above 33 kW/m. Very significant profit potential exists in higher wave climates. Taking moderate cost savings and power efficiency increases into account, Wave Dragon power price will be 0.04€/kWh in 7-10 years time.

FUTURE DEVELOPMENT

Planning for deployment of a 4-7 MW power production unit outside Milford Haven in Wales by 2007 is in progress and wave tank tests of a second generation Wave Dragon with secondary hydraulic power take off systems are ongoing. A multi MW second generation Wave Dragon prototype project has recently been approved by EC's 6th framework programme.

The profitability of the Wave Dragon technology will - as outlined above - improve due to continuous technological development of the Wave Dragon technology; and Wave Dragon will in the longer perspective be scaled the up for more energetic wave climates.

CONCLUSION

A prototype of the Wave Dragon is, as part of the preparations towards a full size multi MW production plant, undergoing real sea testing in Nissum Bredning, Denmark. So far the preliminary testing has supported the data earlier achieved from laboratory testing of mainly hydraulic performance and forces.

Furthermore, invaluable experience has been obtained in most operational aspects, such as regulation strategies for crest freeboard and turbines, remote control of operation and testing, etc. Also problematic design details have been pointed out, and solutions tested in realistic conditions.

For further information: www.wavedragon.net

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The following companies have sponsored part of the prototype: Siemens (SCADA), Ginge-Kerr A/S (argonite system), Hempel A/S (painting), Hydro Group Plc. (subsea cable), Danfoss A/S (water hydraulics), ITT Flygt (propeller pump), Fiberline Composites A/S (trash rack).

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Table 1
Dimension of Wave Dragon prototype and Wave Dragons for different wave climates

Unit size	Prototype	24 kW/m	36 kW/m	48 kW/m	60 kW/m
Width (between reflector tips), m	57	260	300	390	390
Weight incl. ballast, t	237	22,000	33,000	54,000	54,000
Reservoir, m^3	55	5,000	8,000	14,000	14,000
Number of turbines	1+3+6	16	16-20	16-20	16-24
Annual power production, GWh/year	0.06	12	20	35	43
Generators (PMG), kW	2.5	250	350-450	460-700	625-940

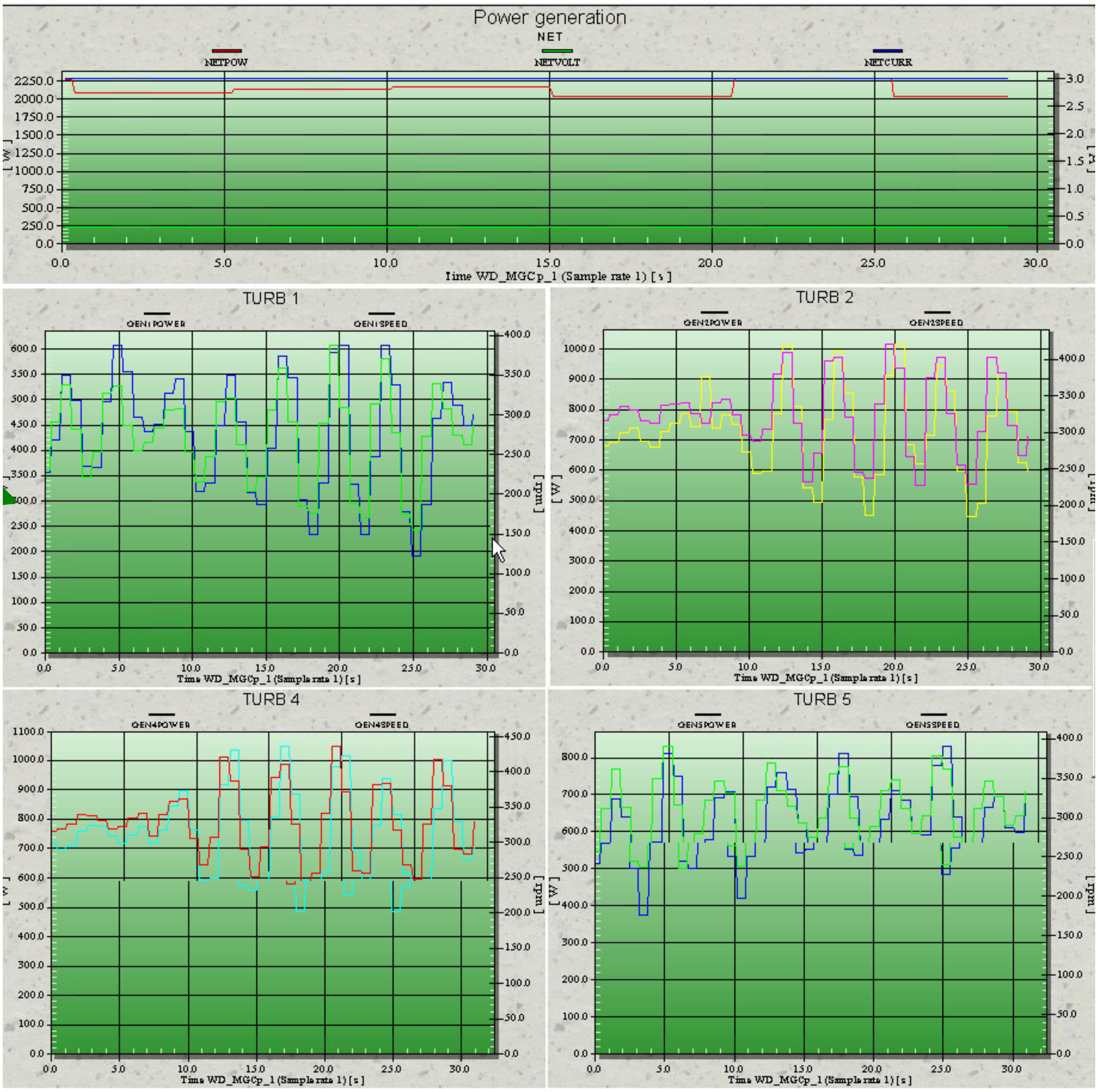

Figure 16: Power production from 4 turbines shown together with the turbine on-off regulation steps.